

# DEVELOPMENT OF THE NAVSEA / ALLIANT TECHSYSTEMS TACTICAL AIRBREATHING PROPULSION, INTEGRAL-ROCKET/RAMJET-ENGINE TEST FACILITY\*

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## ABSTRACT

This document summarizes the design and installation of an air-breathing engine test facility at the Alliant Techsystems, Inc. (ATK) Rocket Center, WV plant located at NAVSEA's Allegany Ballistics Laboratory (ABL). The design process, requirements, and performance of the new facility are discussed. The purpose of the facility is to provide a state-of-the-art testing capability that addresses tactical air-breathing propulsion and materials testing needs. The facility project, a collaboration of the U.S. Navy and ATK, will enable testing that will address current and future U. S. interests in tactical integral-rocket/ramjet and next-generation propulsion.

The tactical air-breathing propulsion test facility at ATK provides the capability to test integral-rocket/ramjet (IRR) propulsion and heat shield materials over a wide range of flight conditions. The facility provides computer-controlled real-time variable airflow rates, temperatures, and pressures to engine test vehicles for trajectory performance evaluation. The state-of-the-art storage heating system provides clean-air to the test stand at pressures capable of evaluating high Mach, sea level systems. ATK, at its Rocket Center facility, performed detailed analyses of both domestic and foreign air-breathing test systems. Factors such as system architecture (pebble bed versus vitiated), capacity, efficiency, service life, and maintenance were evaluated. The ABL system was designed by GASL, a division of Allied Aerospace. GASL's extensive testing background for such agencies as DARPA, the Air Force, and NASA, provided unique user-based experience and lessons-learned in the test facility's design. The initial phase of the system, to be completed this year, will provide 60-lbm/sec airflow at a max operating temperature of 3000 R. Subsequent phases address altitude simulation and instrumentation. The system provides 1500-psia airflow to the test article via high-pressure, internally insulated hot-flow piping. Nearly 2000-lbm of usable air is available which will provide full duration testing for most foreseeable, air-launch, and kinetic energy (KE) applications. The airflow capacity can be easily upgraded as the need arises, and the system was designed to provide adequate heating capacity for these future requirements.

Air-breathing tactical propulsion addresses the need to develop lighter weapons, with longer ranges, and reduced time to target. ATK has been involved in the area of solid propellant, variable flow ducted rocket technology since the late 1960's. ATK innovations provided many contributions to the Air Force Variable-Flow Ducted Rocket (VFDR) AMRAAM program. These developments included hardware fabrication, injector technology, the solid-fuel and fuel delivery system, throttle control valve hardware, and throttle control software. ATK is continuing its heritage in tactical air-breathing propulsion at its Rocket Center, WV location.

## INTRODUCTION

### HISTORICAL BACKGROUND OF ATK TESTING CAPABILITY

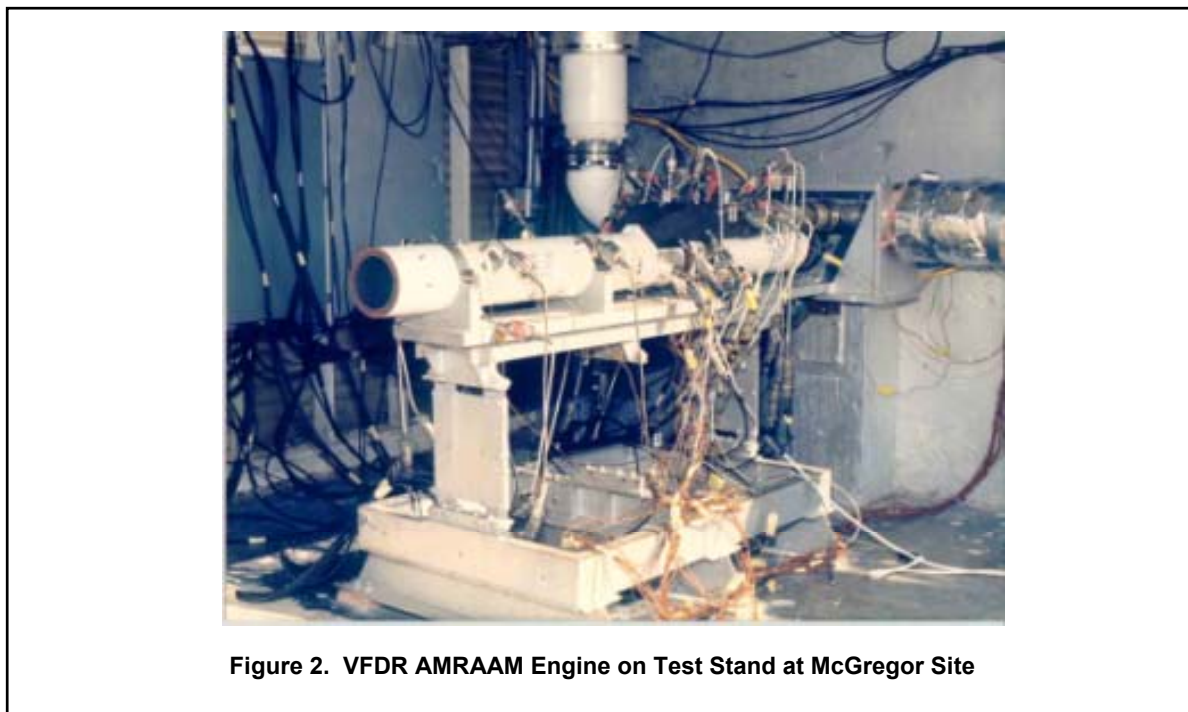
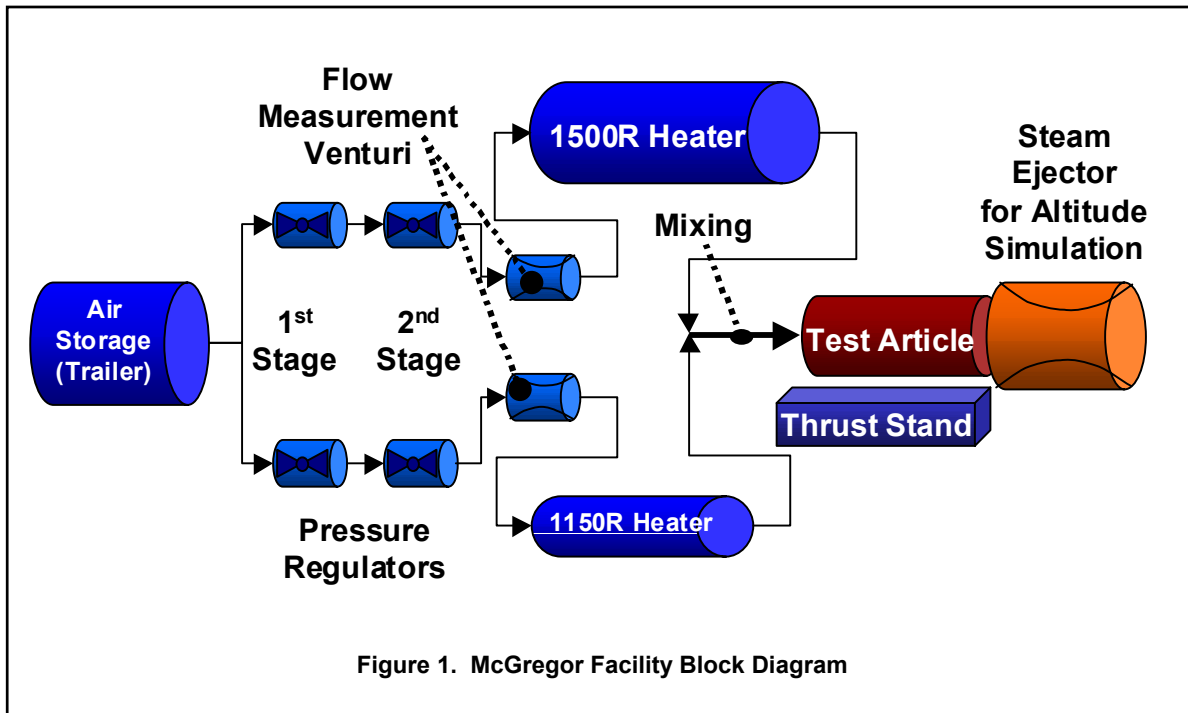
Much of what is now considered the field of air-breathing tactical propulsion began at the ATK (formerly Hercules, Inc) plant in McGregor, Texas. Direct-connect engine facilities were constructed on site to provide accurate and cost-effective ramjet engine development assessment. This facility was a simple, direct-connect, blow-down static test firing area for tactical-class ramjet engines. Standard atmospheric air was provided to the facility by a tube trailer containing 30 cylinders having a storage volume for 1527 standard cubic feet (SCF) of air. Approximately 3500-lbm of air was stored at 2400 psia. Additional air was available for testing larger, longer-duration ramjet systems. Typical full-duration VFDR AMRAAM (7-in. class) tests – including pre-fire and post-fire run-ups – required 400 to 600 lbm of air. A block diagram of the facility layout is provided in Fig. 1. Approximately 85% of the VFDR AMRAAM engine tests were performed at this facility. A VFDR AMRAAM ramjet engine is shown on the test stand in Fig. 2.

During a ramjet engine test in the McGregor facility, air from the trailer entered the test facility through a single 3-in. feed line, which then split the flow into two smaller 2-in. feed lines. The air passed through dual-stage pressure regulators to provide a constant pressure to the system, even though the storage tank pressure was diminishing during operation. The regulators also ensured that system pressure never exceeded the design pressure of the pebble bed heating vessels. Each of the smaller 2-in. lines fed an adjustable single-set-point regulator that

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\* Previously Published in the Proceedings of the 26<sup>th</sup> JANNAF Airbreathing Propulsion Subcommittee, Destin, FL, April 8-12, 2002. Distribution is Unlimited. Cleared for Public Release.

Report Documentation Page			Form Approved OMB No. 0704-0188		
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1. REPORT DATE <b>00 APR 2002</b>		2. REPORT TYPE <b>N/A</b>		3. DATES COVERED <b>-</b>	
4. TITLE AND SUBTITLE <b>DEVELOPMENT OF THE NAVSEA / ALLIANT TECHSYSTEMS TACTICAL AIRBREATHING PROPULSION, INTEGRAL-ROCKET/RAMJET-ENGINE TEST FACILITY</b>			5a. CONTRACT NUMBER		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER		
			5d. PROJECT NUMBER		
6. AUTHOR(S)			5e. TASK NUMBER		
			5f. WORK UNIT NUMBER		
			8. PERFORMING ORGANIZATION REPORT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>ATK Tactical Systems Company Rocket Center, West Virginia and Allied Aerospace Industries, Inc., GASL Division Ronkonkoma, New York</b>					
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSOR/MONITOR'S ACRONYM(S)		
			11. SPONSOR/MONITOR'S REPORT NUMBER(S)		
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Approved for public release, distribution unlimited</b>					
13. SUPPLEMENTARY NOTES <b>See also ADM201519., The original document contains color images.</b>					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT <b>UU</b>	18. NUMBER OF PAGES <b>11</b>	19a. NAME OF RESPONSIBLE PERSON
a. REPORT <b>unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>			



reduced trailer pressure to a constant intermediate value of choice. Air at this reduced pressure entered a programmable regulator, which controlled air pressure to a downstream metering venturi according to a preset schedule. The dual-stage regulation greatly enhanced the precision tracking of the command pressure profile. Each of the two lines could pass a maximum 11-lbm/sec airflow, thus giving the facility a maximum capability of 22 lbm/sec. The air storage tanks are illustrated in Fig. 3.



**Figure 3. McGregor Site Air Storage Tanks**

The dual airflow lines ran through independent metering venturi stations and through electric pebble-bed heaters. One line dumped air into a heater with a capacity of 1150 R, while the other line ran through a larger heater with a capacity of 1500 R. Piping from the heaters to the test article was electrically heated and insulated to minimize temperature losses. By using different pebble-bed heater temperature set points and mixing air from each of the two lines, the total air flow rate and delivered temperature of the air to the test article was modulated to simulate dynamic flight trajectories. By providing total temperatures up to 1500 R, the facility effectively could achieve Mach 3 sea-level conditions and Mach 3.8 at higher simulated altitude. The large capacity pebble bed heater is shown in Fig. 4.



**Figure 4. McGregor Site Large Capacity Pebble-Bed Heater**

## DESIGN CONSIDERATIONS

### NEXT-GENERATION PROPULSION REQUIREMENTS

Tactical air-breathing propulsion provides solutions with extended range capability and increased average flight speed. With government added emphasis on time-criticality in next-generation propulsion systems, it became apparent to the NAVSEA/ATK team that the environments would be more severe than what could be simulated by the McGregor facility. During the VFDR AMRAAM program the McGregor facility was consolidated and transferred to the NAVSEA Allegany Ballistics Laboratory site in Rocket Center, WV. It was recognized that the benefits of using a facility arrangement similar to the McGregor storage heated facility would provide accurate clean-air ramjet engine test environments, real-time trajectory capability, as well as cost-effective testing for the end user. Also, by using clean-air methodologies at high pressures, the facility could be widely used to generate data for heat shield and aero-thermal research on materials and flight vehicle airframes.

The facility requirements were defined based on the foreseeable tactical propulsion needs for U.S. interest. The facility was developed to be expandable provided the airflow rate and/or temperature requirements change. But most importantly, the unit had to provide realistic, high-performance airflow to the test vehicle, accurately simulating air-breathing engine flight. The zones identified for near-term need are displayed in Fig. 5.

Three zones were identified that generally encompass the foreseeable tactical propulsion need for ramjet propulsion engines. The first and largest zone represents air-launched missiles, such as VFDR AMRAAM and HARM propulsion upgrades. The second, middle, zone identifies foreseeable improvements to the speed of cruise missile systems such as Tomahawk. The third zone identifies the general region to expect supersonic vehicles that provide kinetic-energy-kill capability such as Future Combat System (FCS), or compact KE missile applications. Figure 5 illustrates a Mach-Altitude flight regime and is overlaid with representative lines of constant total temperature. This provides information as to the temperatures expected in subsonic combustion air-breathing vehicles. Airflow capacity is a function of the engine size, primarily, so the facility was designed upgrade-capable to meet these future needs. The primary design consideration became the heating methodology. Many forms were considered, including vitiated and storage heaters, but for ramjet engine takeover at low Mach and high altitude, and high Mach flight at high temperature, only the storage heating systems met future high technology evaluation criteria.

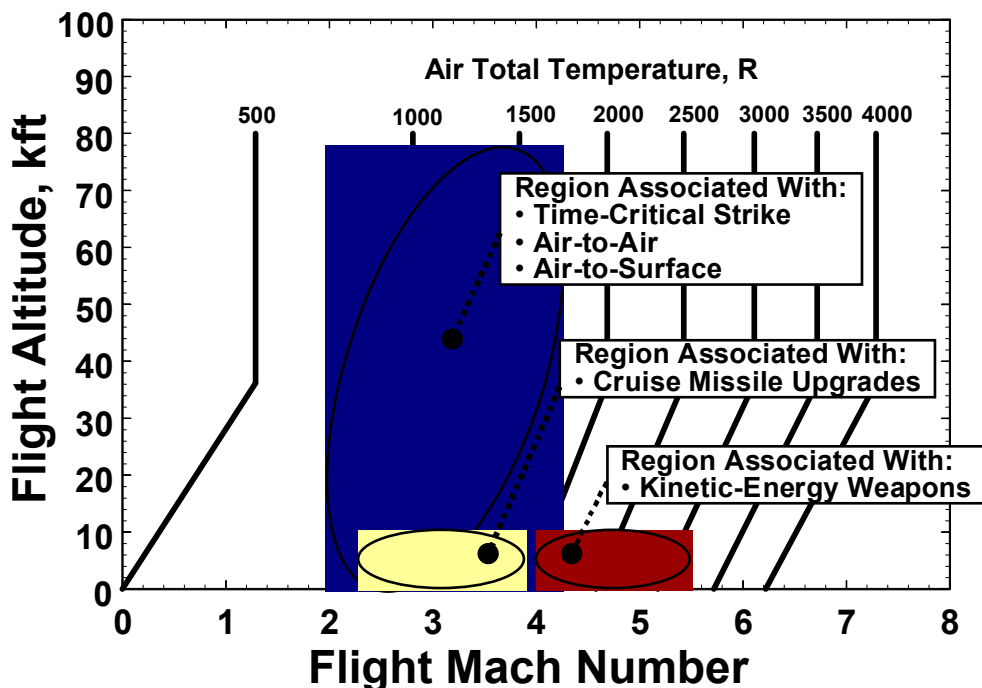
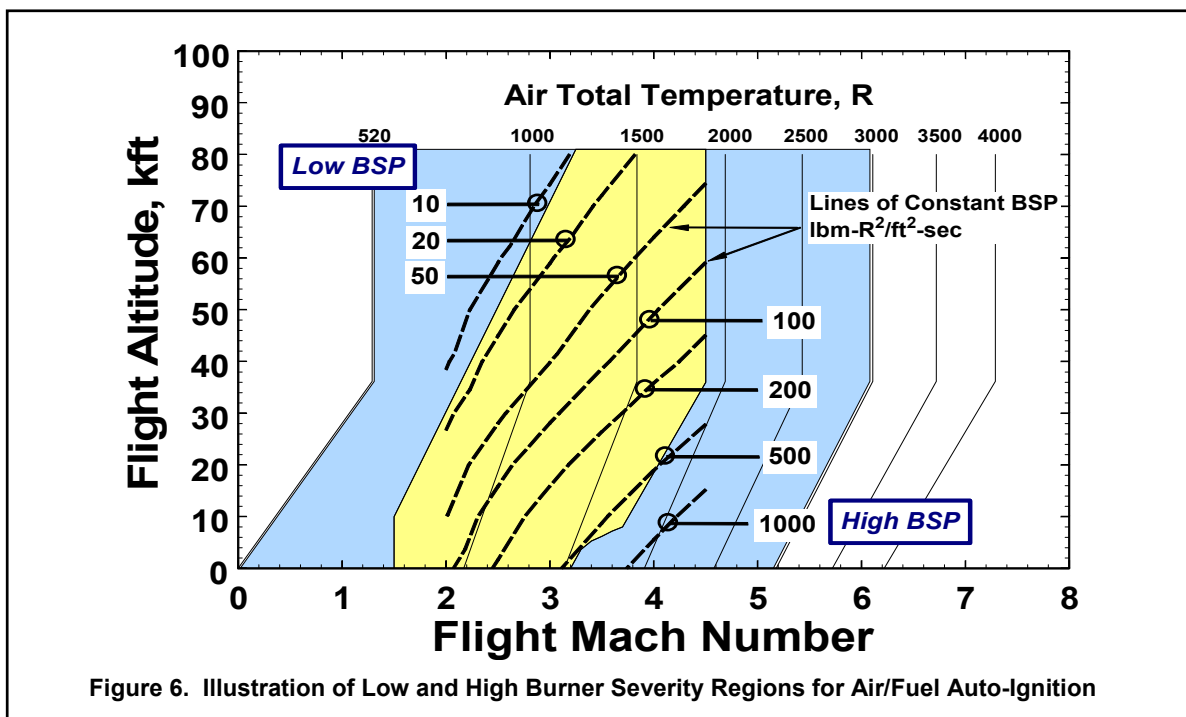


Figure 5. Zones Identified for Near-Term Tactical Propulsion Needs

## AIRFLOW HEATING METHODOLOGY

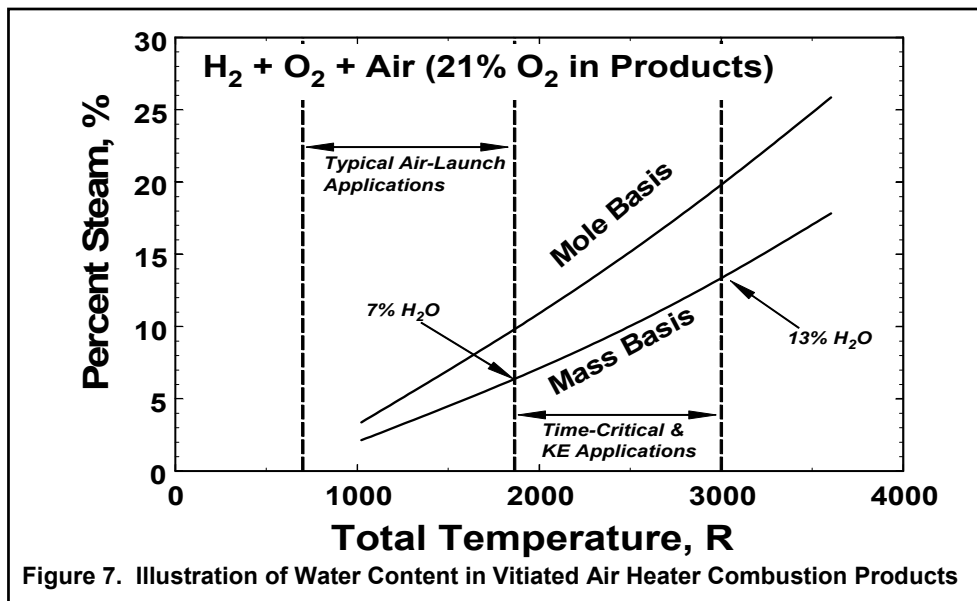
Ramjet takeover is an important feature to consider when evaluating the heating methodology for air-breathing engine test facilities. During actual flight, it is in most cases desired to takeover air-breathing sustain-phase flight as early as possible – particularly when considering tactical missile applications. This affords the vehicle the ability to extract the highest possible delivered mass specific impulse early in the mission. Also, it minimizes the need to use larger rocket boosters for reaching higher takeover Mach numbers. So it is inevitable that the air-breathing engine will require air-fuel auto-ignition capability in regions where ramburner conditions do not necessarily favor spontaneous and rapid ignition, i.e. at reduced Mach numbers. This region, usually at low Mach numbers and somewhat associated with high altitude, is sometimes referred to as the region of low burner severity. The parameter that is typically associated with this condition is designated burner severity parameter (BSP). This is illustrated in Fig. 6. The figure shows a light region in the middle that represents a typical ramjet designed for air-launch applications.



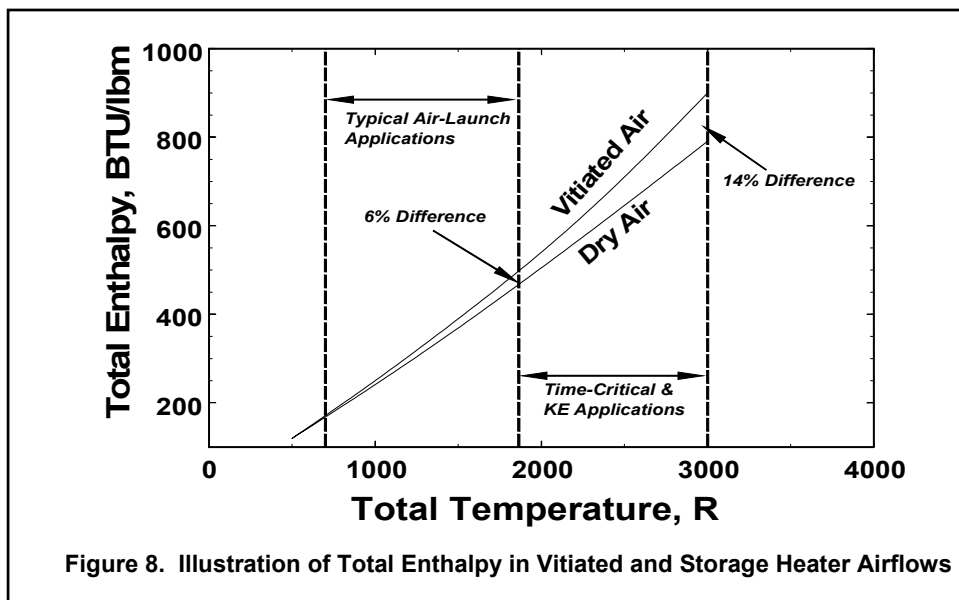
Storage heaters provide more realistic environments for testing air-breathing engines than do vitiated, or combustion, heated systems. In storage heated systems, clean air is flowed directly through a preheated ceramic-pellet bed (or in some cases metal spheres are used). Vitiated systems generate airflow temperature by chemically reacting excess-oxygen with either hydrogen or a hydrocarbon in airflow. The end result provides hot, 21% oxygenated exhaust to the test article. Storage heating can provide temperatures around 4500 R using modern design, therefore, hypersonic Mach numbers can be simulated effectively using these heaters. The drawback to storage heaters is primarily one of cost and space. Since storage units can become expensive and bulky, the preferred approach over the years has been vitiated air, heated directly on the thrust stand in a smaller vessel.

Key to the successful evaluation of the tactical ramjet or ducted rocket is the accurate assessment of the low Mach and high altitude region during air-breathing takeover. The complete success of an air-launched system depends highly on its performance in the cold, low airflow environments of the upper left corner of the flight envelope. In Figure 6, the upper left corner of the envelope is designated Low BSP which represents the combustion limit region for the typical air-launched, ducted rocket engine. The lower right envelope is designated High BSP and represents favorable combustion environment. The lines between show BSP calculated for a representative fixed geometry ramjet engine. BSP, as shown in the figure, is a function of only the air total temperature and captured airflow rate for the fixed geometry engine. Vitiated systems have historically been difficult in regions of low and high BSP. First, the generated gas flow relies on combustion to provide some of the airflow mass and heat. Therefore, maintaining low temperatures can be difficult. On the other side of the envelope, the high BSP airflow becomes highly tainted with water vapor among other byproducts.

Today, testing engines to enthalpy or temperature remains an open question for vitiated systems. This argument is avoided by using the storage heating methodology. For example, Fig. 7 displays the water content found in a vitiated airflow for the hydrogen-oxygen combustion-heated system. The assumption is that once combustion is complete, the airflow maintains the appropriate temperature as it enters the engine and the oxygen content represents that of theoretical air (21% by mass). Data is presented on a %-mass and %-mole basis. Regions have been designated for *air-launch* and *time-critical* systems. The temperature range identified represents the air total



temperature experienced by those systems during normal operation. The vitiated airflow for air-launch systems can contain nearly 7% H<sub>2</sub>O by mass. Air-breathing time-critical systems will see as much as 13% H<sub>2</sub>O if evaluated on the vitiated system. The historical argument associated with the water vapor in the products is directed toward one of enthalpy versus temperature when testing air-breathing engines. Figure 8 illustrates the effect H<sub>2</sub>O has on the



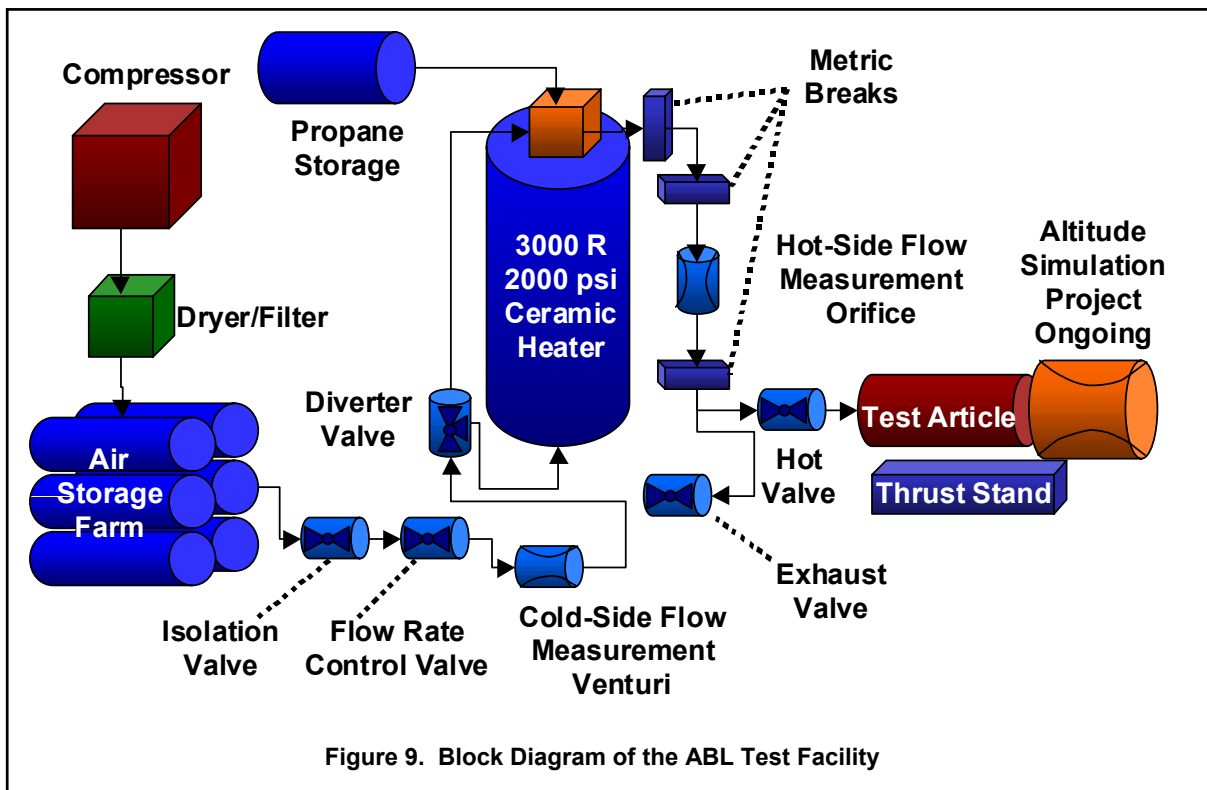
enthalpy of the vitiated air stream. The vitiated airflow containing water vapor can have as much as 14% more enthalpy at 3000 R than dry air streams at the same temperature. These analyses were performed using CET86001, the Nasa-Lewis Thermochemical Equilibrium computer program.

Tests have shown that some hydrocarbon fueled ramjet engines, particularly solid-propellant ducted rockets, experience misleading, and sometimes significant performance boosts using vitiated systems. Even with a properly vitiated airflow, the combustion products can contain significant quantities of carbon dioxide (hydrocarbon vitiators only) and water. With normal hydrocarbon-fueled ramjet engine testing, this generally is not a problem. However, highly metallized fuels, such as those found in ducted rockets or solid-fuel ramjets, sometimes react readily enough to use the  $\text{CO}_2$  and  $\text{H}_2\text{O}$  as oxidizers. The more reactive the metal, the larger this very misleading effect. Magnesium fuels are particularly notorious for experiencing this performance augmentation. In summary, due to the history of the data accuracy involving vitiated systems, the storage heater method using clean air was selected.

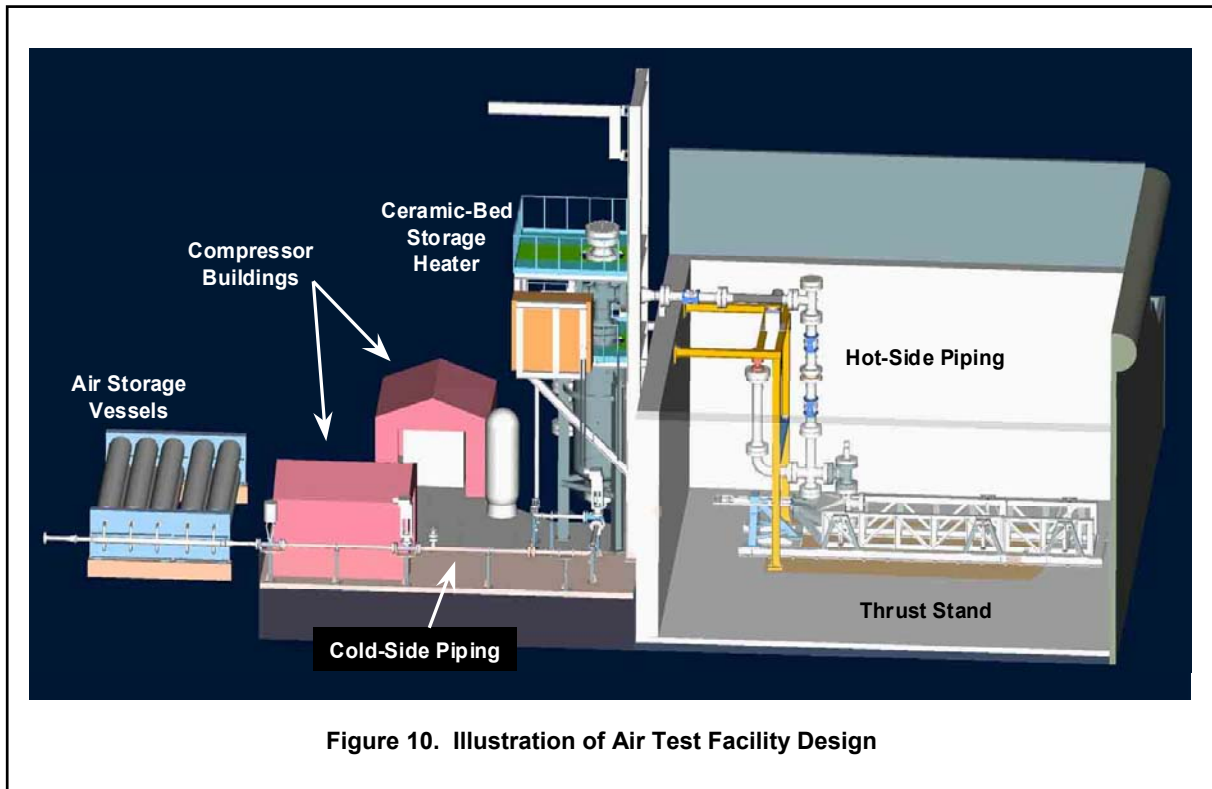
#### NAVSEA FACILITY LAYOUT AND DESIGN DESCRIPTION

The ABL facility storage-heated layout was selected to provide the most accurate ramjet test environment possible for foreseeable next-generation tactical propulsion. Airflow capacity can be upgraded to provide compliance with larger systems as these programs emerge. Should temperatures be required in the hypersonic regime, the state-of-the-art heating methods at that time can be employed downstream of the existing storage heater to provide boost to the desired total temperature. Currently, this is done in practice at Allied Aerospace, Inc. in the GASL-division's Leg-IV facility at the Ronkonkoma, NY site. GASL maintains a storage heater with downstream vitiation system to provide hypersonic test capability while minimizing the effects of vitiated airflow. This provides a most accurate testing environment for the hypersonic regime.

Real-time trajectory capability is desired so that a minimum number of tests can be run to map engine performance. Many existing systems use a point-test methodology to provide ramjet performance at a discreet flight altitude, Mach number, and angle of attack – upon which more tests are required to evaluate all of the points along a desired trajectory. By using updated computer controllers and a cold-flow heater bypass system, the ability to modulate temperature, along with flow rate and pressure, real-time during a single test was developed. The block-diagram of the facility is displayed in Fig. 9. An isolation valve just downstream separates pressure from the storage system and the test system from the tanks. A flow control valve and venturi measure airflow rate on the cold-air side just prior to entering the heating system. The measured cold flow is then directed through a three-way diverter valve where a portion of the flow is directed through the heater. The remaining flow bypasses the heater and is mixed with the heated flow downstream to provide the desired temperature. The design that matured from the block diagram is presented in Fig. 10. The facility is constructed in the ABL Bay 4 test area. Test Bay 4 provides complete tactical



propulsion test capability in that it is designed for solid propellant rocket motor systems, providing support for such systems as Hellfire and upper stage Polaris testing. The entire Cold Side piping system, compressors, and storage heater is located outside of the bay behind the primary thrust wall. The Hot Side piping system is located within the test bay along with the ramjet thrust stand. The NAVSEA test system has undergone both thermal and structural analysis and has been designed in accordance with ASME and ANSI specifications.

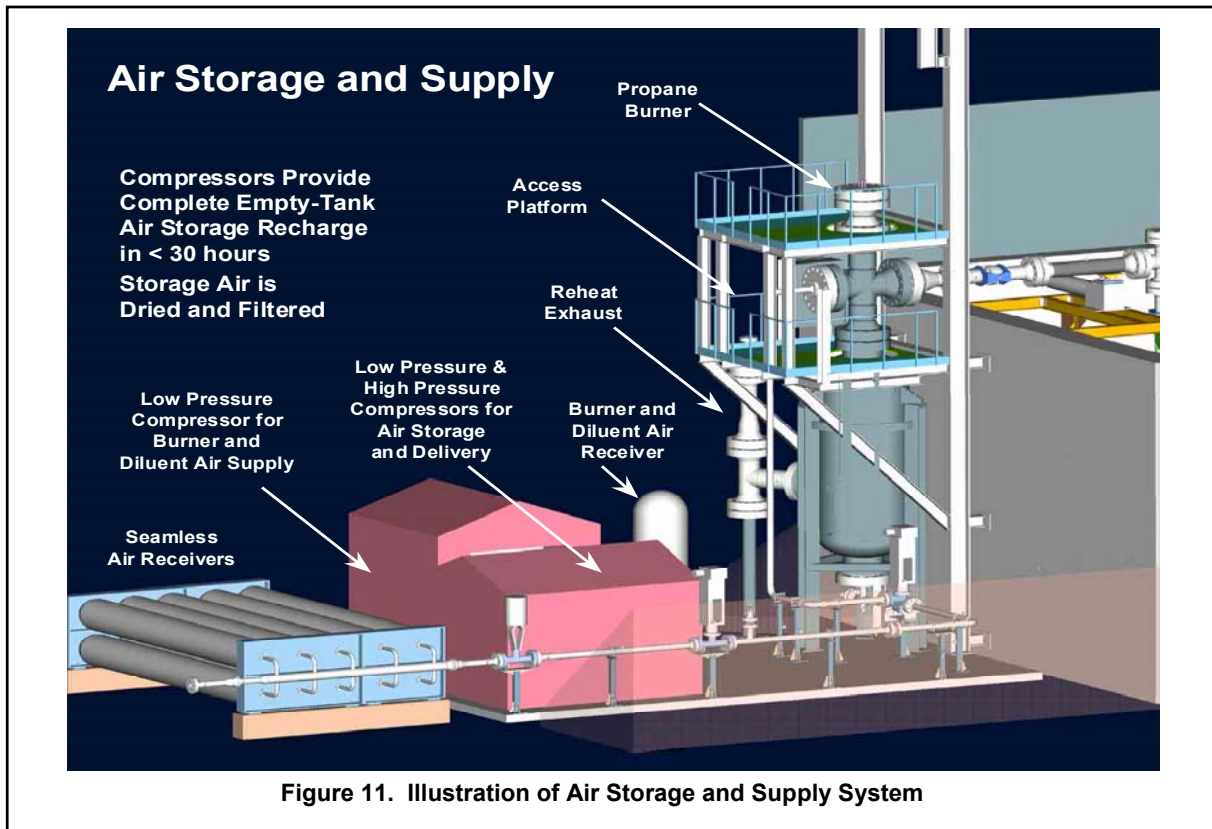


**Figure 10. Illustration of Air Test Facility Design**

#### AIR STORAGE AND SUPPLY

The Air Storage and Supply system comprises the air storage tanks (vessels) and the compressor system. The primary test-air storage farm consists of 10 seamless receivers that provide over 2000 lbm of usable airflow to the test facility. The designed Air Storage and Supply system is illustrated in Fig. 11. The primary storage vessels were fabricated to a temperature range of  $-40^{\circ}\text{F}$  to  $+200^{\circ}\text{F}$ . Manufactured from SA372 Grade-J Class-70 carbon steel, the seamless construction provides a design pressure of 3700 psig. The vessels are 24-in. diameter and 20 feet long.

The receivers are charged by a dual compressor system that stages the air to 3000 psia. The compressors are located in a utility building next to the air receiver farm. The low-pressure compressor is a 7.5-horsepower reciprocating compressor with 80-gallon vertical tank and a 175-psi maximum pressure rating. The unit is 510 lbm and stands 70 inches tall. The high-pressure system that stages the air to the tanks is a 15-horsepower, radial, 4-stage reciprocating compressor. The unit is air and oil cooled and provides a maximum operating pressure of 6000 psi. The 400-lbm unit stands 30 inches tall. A dual-tower heatless regenerative air dryer provides conditioning to the compressed air prior to tank storage. The dew point rating of the dryer is  $-100^{\circ}\text{F}$ .



**Figure 11. Illustration of Air Storage and Supply System**

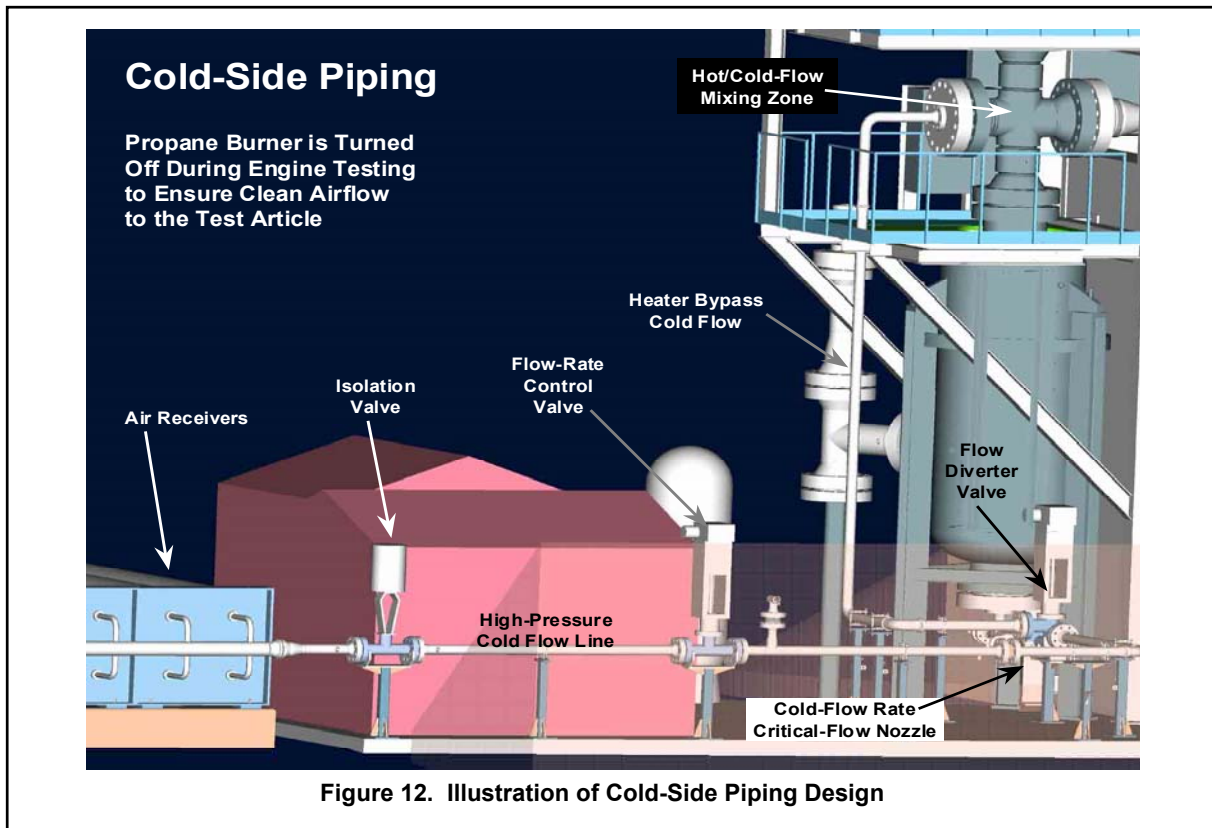
#### COLD SIDE DELIVERY SYSTEM

The Cold-Side Piping delivers air from the storage receivers to the ceramic-bed heater. This is shown in Fig. 12. The primary components of this system consist of the piping, an isolation valve with bypass, a flow control valve, a critical flow measurement nozzle, a diverter valve for air temperature control, pressure relief devices, and state-of-the-art instrumentation and controls. The piping is 4-in. Schedule-160, 3500-psi rated, from the air receivers to the critical-flow nozzle. After the flow measurement nozzle, the piping is 4-in. Schedule-80 rated to 2000 psi. The isolation valve is a 316 stainless-steel 3600-psi globe valve that separates the test system mechanically from the receiver system. The isolation valve is pneumatically actuated. The electro-hydraulically-actuated flow control valve is a split-body globe valve rated to 3600 psi. The valve provides the desired/controlled mass flow rate of air to the system. The electro-hydraulically-actuated diverter valve directs a portion of the cold airflow through the heater assembly while allowing a portion to bypass the heater. The two airflow streams are mixed downstream (the top "T", or "cross" of the heater) to provide the desired temperature test airflow. The valve is a three-way globe valve rated to 3600 psi. Constructed of 316 stainless steel, the valve is designed to fail in the open mode, which diverts all airflow around the heater. Both electro-hydraulically-controlled valves have positioning accuracy to 0.15% in self-contained, single unit designs. They are microprocessor controlled for reliability and flexibility.

#### STORAGE HEATER AND BURNER

The storage heater acts as a capacitor, holding large quantities of thermal energy until it is extracted on demand. Unlike vitiated heating that provides instantaneous on command heated airflow, the storage heater must be preheated prior to test cycles. The pre-heat function is achieved using a propane burner system. The storage heater is displayed on the right side of Fig. 12.

The heater is designed to a pressure of 2000 psig at 650°F, or 1110 R, vessel bulk temperature. This design pressure ensures, after Hot-Side Piping flow losses, that 1500 psi will be delivered to the test stand if desired. The burner assembly is anchored on a tri-pod stand, resting on leg-mounted leveling jackscrews. The vessel has a 60-in. outer diameter cavity with 3-in. wall thickness. The primary vessel is approximately 170 inches from end to end and is manufactured of SA-516 normalized Grade-70 steel. The vessel wall is lined with castable insulators, ceramic insulating board, Firebrick, and ceramic insulators. A grate in the lower elliptical vessel head provides support for the ceramic heat-storage media. The grate temperature is monitored with thermocouples to prevent vessel overheating.



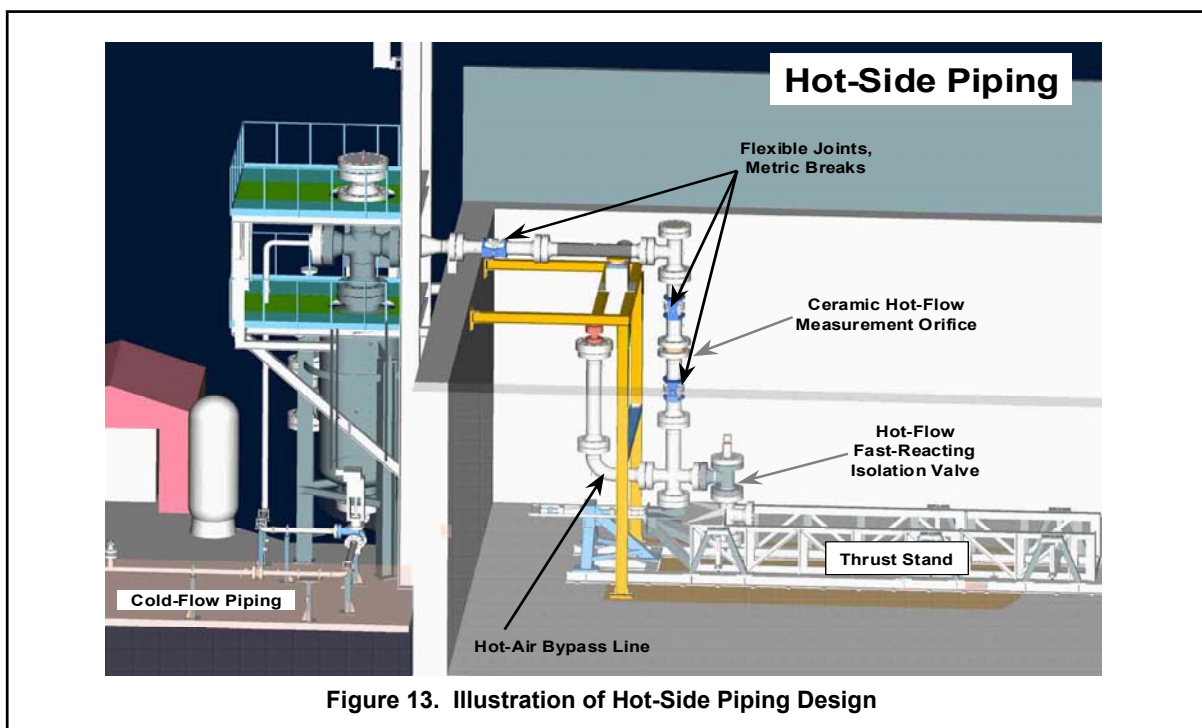
**Figure 12. Illustration of Cold-Side Piping Design**

The heat storage media is comprised of aluminum oxide spheres with a mean outer diameter of 0.75 in. This provides the heater with a maximum rated temperature capacity of 3000 R. Cold airflow enters the vessel from the bottom and flows vertically in the direction of positive buoyancy (up-flow). Proper design was employed to ensure the ceramic bed would not float during high air mass flow conditions when large vertical pressure drops are experienced.

A propane-fired burner mounted at the top cross of the heater assembly heats the storage-heater media. The maximum design reheat time is 24 hours for the ceramic bed. A propane source and compressed air feed the burner. A building next to the heater assembly contains a single large-capacity compressor that provides air to the burner by way of a single air receiver. The propane burner operates at atmospheric conditions. High-pressure block-and-bleed valves isolate the low-pressure hardware during high-pressure heater operation. The flame is ignited and burns with 20% excess air in the primary stage of a dual-stage modulated flame system. The flame temperature at the primary flame front is approximately 3560 R. The secondary stage modulates the flame temperature with diluent air. The flame temperature then becomes 3260 R or less – depending on desired bed temperature. The flame flows down through the ceramic heater storage media heating the spheres to the desired condition. Exhaust flows through a side-mounted port in the heater vessel wall. The side-mounted exhaust helps to keep the high temperatures away from the lower elliptic dome head and keep the support structure cool. The presence of flame in the burner is supervised and confirmed using ionization detection. When the heater reaches the desired temperature, the burner is shut down and purged so that no propane or exhaust enters the test article. The vessel contains 21 threaded instrumentation ports, 2 columns of thermocouples 180° apart, 4 ports in cross to monitor gas temperature and pressure, and 3 ports in the bottom elliptical head.

#### HOT SIDE DELIVERY SYSTEM

The Hot-Side Piping delivers the heated air from the mixing-cross to the test article on the thrust stand. This is illustrated in Fig. 13. The Hot-Side Piping consists of the airflow piping with bypass line, flexible joints, a flow measurement orifice, and fast-reacting isolation valve. The piping in this section of the system must be insulated, not only to provide the pipe with structural integrity, but also to minimize temperature droop in the airflow during the route from the heater to the test stand. Pipe preheating is accomplished prior to a test by allowing air to flow through the piping system by way of a bypass line. This minimizes the effect of airflow temperature loss during a test, otherwise known as droop. The hot-side piping itself is 10-in. outside-diameter stainless steel Schedule-120 insulated with 1-in. ceramic insulation. The inside, insulated 7-in. diameter of the pipe is such that the maximum expected Mach number is 0.20. In normal operating modes, the Mach number will remain less than 0.05 through most of the testing. The piping is rated to 2350 psi at 650°F. The hot-side piping contains 5 thermocouples and 2 pressure taps for accurate tracking of system hot-side performance.



**Figure 13. Illustration of Hot-Side Piping Design**

Three high-pressure flexible joints are included in the hot-side piping system. The joints use a bellows with a hinged-side plate design to provide axial continuity while remaining flexible in one axis of bending. Piping system pressures are internally self-balancing using this design. Therefore, no pipe pressure loads are reacted by the vessel or the test stand. By using three flexible joints with bending flexibility, pipe thermal growth in the vertical and horizontal axes are accommodated without imparting loads to the test stand. This flexibility acts as a metric break for thrust measurement.

A sharp-edge flow orifice made of graphite construction utilizing silicon-carbide coating is used for accurate assessment of real-time flow rate to the test article. The orifice is designed to ASME standard using 2 pressure taps and 1 thermocouple. The orifice area increase due to thermal growth is approximately 0.39%. Based on this increase the accuracy of flow measurement is 0.20%.

During development of specifications for the facility, it was recognized that a fast-acting hot-side valve would be necessary to quickly turn the test airflow on and off. This action is required for proper simulation of next-generation kinetic energy weapons and for testing materials and heat shields. For optimization of insulators, systems will need to examine the thermal response only for the expected flight time. If too much insulation is designed on, and applied to, a vehicle in production, whether it is ramjet combustor insulation or an external aeroheat barrier, then vehicle flight performance and manufacturing cost is compromised. The Hot-Side Fast-Reacting Isolation Valve consists of a fixed throat and a hydraulically actuated pintle. The pintle is designed to be completely out of the flow when fully retracted to avoid thermal failure. The time between flow restriction of the valve and the full closed position is only 0.5 second. The plug is of graphite construction with silicon carbide coating.

#### FUTURE PLANS AND ONGOING WORK

The NAVSEA/ATK project, as just described, is moving close to facility shakedown and calibration. Instrumentation is currently being acquired to provide pertinent ramjet data for analysis of total engine performance. Of primary interest, other than standard thrust stand equipment, are Schlieren photography systems and nozzles to provide free-jet and heat-shield testing capabilities. Work is also underway to provide the necessary altitude simulation capabilities for ramjet direct-connect and free-jet testing modes. Altitude simulation capabilities are pertinent to evaluate ramjet performance during conditions when combustion chamber pressures are low.

#### SUMMARY AND CONCLUSIONS

The purpose of the facility is to provide a state-of-the-art testing capability that addresses tactical air-breathing propulsion and materials testing needs. The facility project, a collaboration of the U.S. Navy and ATK, will enable the NAVSEA Allegany Ballistics Laboratory to conduct testing that will address the current and future interests in tactical integral rocket ramjet and next-generation propulsion. Modern storage heating methods and design practices were utilized to provide accurate flow simulation to a test article. Data integrity and simulation flexibility was considered toward ensuring quality testing for future U.S. tactical propulsion needs.